Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 80 (2019) 334–339

www.elsevier.com/locate/procedia

26th CIRP Life Cycle Engineering (LCE) Conference

Life cycle environmental impacts of natural gas drivetrains used in road freighting

Jasmin Cooper[a,b*], Paul Balcombe[a,c]

[a] Sustainable Gas Institute, Imperial College London, London, SW7 1NA, UK
[b] Department of Earth Science and Engineering, Imperial College London, London, SW7 2AZ, UK
[c] Department of Chemical Engineering, Imperial College London, London, SW7 2BP, UK

* Corresponding author. Tel.: +044-020-759-47406 . *E-mail address:* jasmin.cooper@imperial.ac.uk

Abstract

The displacement of diesel in the road freight sector by natural gas could cut the sector's environmental impacts but methane emissions risk eliminating this benefit. A life cycle assessment has been performed to compare natural gas fuelled trucks to diesel, biodiesel, dimethyl ether and electric (UK grid mix), on impacts to climate change, air quality and resource depletion. LNG drivetrains exhibit climate change impacts lower than diesel (17-21%) and similar to electric drivetrains, but CH_4 emissions will negate any benefits if they exceed 3.5% of throughput for typical fuel consumption. However, this is much higher than measured slip from current natural gas trucks. Biodiesel exhibits the lowest GHG emissions but for compressed natural gas, only at lowest fuel consumption and negligible methane emissions does this option reach climate parity with diesel. For the other indicators, natural gas exhibits lower impacts (11-66%) than diesel and is the best performer for all the indicators while electric and biodiesel are the worst.

Keywords: natural gas; life cycle assessment; heavy duty trucks; road freight; climate change, global warming

1. Introduction

In 2015 the road freight sector contributed 8% towards global greenhouse gas emissions and 26% of all vehicles in use [1-3]. The sector primarily relies on diesel to fuel its fleets but in recent years, strict regulations have been imposed to curb tailpipe emissions, targeting CO_2, nitrogen oxides (NO_x) and particulates amongst others [4]. These regulations, as well as volatility in the price of diesel [5, 6], have led to freight companies looking for alternatives fuels such as biodiesel, as well as alternative technologies such as batteries (electric vehicle) [2]. However, biodiesel suffers from issues associated with feedstock cultivation (e.g. crop competition, water use and land use) [7], while electric trucks suffer from low travel range and lack of charging infrastructure [8]. An alternative to these is natural gas, which could offer emissions reductions over diesel while lower emission technologies and fuels are further developed.

Natural gas produces three quarters the CO_2 of diesel and gasoline upon combustion and generally negligible quantities of other air pollutants [9, 10]. It has been used as a transport fuel since the 1930s [11] and is traditionally cheaper (per unit energy) than crude oil derived fuels [12]. Natural gas powered vehicles (NGV) use engines similar in design to diesel and many conventional vehicles can be retrofitted to use natural gas [13-15]. In the past decade, the number of NGVs has increased by 2.6-fold, with China seeing the biggest growth and in 2018 there were over 26 million NGVs in the world with most being found in China (5.4 million), Iran (4.5 million) and India (3.1 million) [16].

The majority of previous studies on NGVs has focused on personal vehicles rather than heavy goods vehicles (HGVs)

10.1016/j.procir.2019.01.070

and typically compared it (either as compressed natural gas (CNG) or liquefied natural gas (LNG)) to diesel or gasoline [17-24]. All studies consider impacts to climate change, measured through the global warming potential (GWP) and some consider other impacts, such as cost effectiveness and air quality. In terms of HGV focused studies, to the authors' knowledge there are only three peer reviewed life cycle studies: Arteconi, et al. (2010) [17], Beer, et al. (2002) [18] and Cai, et al. (2018) [20], which compare natural gas powered HGVs to diesel on GWP. In addition, the UK's Department for Transport (DfT) commissioned a series of reports to assess the potential for natural gas as a fuel for the nation's HGV fleet (also in comparison to diesel) [25-27], based on GWP and NO_x emissions. The GWP reported in the literature vary in the range 0.67-1.76 kg $CO_{2\text{-Eq}}$/km with the GWP being sensitive to methane emissions. Fugitive emissions in the supply chain and fuel station are traditional sources but methane slip (unburnt methane passing through the engine) has been identified in both the peer-reviewed and non-peer reviewed literature as an important source of emissions. The DfT reports calculated 2.6 g/km of methane slip [25-27] to be enough to increase the GWP of retrofitted dual fuel trucks to that of diesel.

This study adds to the current body of literature by conducting a life cycle assessment (LCA) of CNG and LNG as a HGV fuel, including a full suite of environmental impacts and comparing to diesel and other alternative fuels. This work is of interest to fleet operators and transport policy makers as well as HGV manufacturers. The methodology, data and assumptions used to conduct this research is presented in the next section, followed by the presentation and discussion of the results followed by the conclusions drawn.

2. Methodology

To assess the environmental impacts of natural gas drivetrain HGVs, an LCA is conducted following the steps outlined in ISO 14040/14044 [28, 29]. A system boundary from 'cradle to grave' is considered, taking into account the whole fuel cycle, from production/extraction to use in the vehicle (Figure 1). The impacts were calculated based on literature fuel economy/consumption values and impacts to climate change, air quality and resource depletion are considered. The study does not consider driving regimes, the effect of varying loads or driving on different types of roads, although the percentage of urban driving is considered. Spark ignition (dedicated fuel) and dual fuel engines are considered, as these are the only engine types with sufficient data on fuel consumption and tailpipe emissions. Two methods for delivering LNG are considered; transport of LNG to the fuel station in a cryogenic trailer and onsite liquefaction. For CNG, only onsite compression is considered. To assess the impacts, the functional unit of 1 km distance travelled by an HGV has been used.

In total, seven fuel options are considered:

- compressed natural gas (CNG; compressed at fuel station);
- liquefied natural gas (LNG; liquefied and delivered by trailer);
- dual fuel (diesel and LNG; LNG liquefied and delivered by trailer);
- diesel (baseline);
- biodiesel (from soybean);
- dimethyl ether (from natural gas); and
- electricity (battery; 2016 UK electric mix).

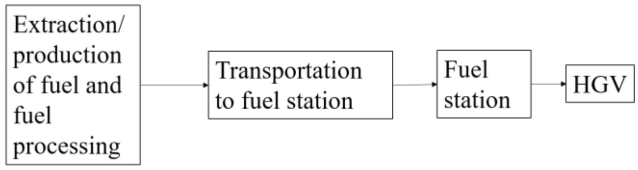

Figure 1: Life cycle system boundaries of fuels considered in this work. System boundaries are from 'cradle to grave'. The construction of the HGV body is also considered.

2.1. LCA modelling

The LCA was modelled using GaBi v8 software [30], using data from the ecoinvent 3.3 dataset [31] for upstream processes and GREET [32] to collect data on HGV tailpipe emissions. Literature data on fuel consumption and share of travel on urban roads (based on UK conditions) (Table 1) were also used to build the GaBi models. In addition to the HGVs, process models were also built for fuel stations and LNG transport, as well as the upstream stages of the fuel supply chain. For these, literature data were used (Table 2), as well as data from the ecoinvent 3.3 dataset. The fuel station energy consumption considers the energy required to run the fuel dispensing system, as well as energy to compress or liquefy natural gas. Energy for convenience stores, public bathrooms and other facilities are not included. The fuel station infrastructure is not considered as the impacts will be negligible because of the lifespan of service stations and the quantity of fuel dispensed over their lifetime. The biodiesel and dimethyl ether fuel stations are assumed to have the same energy consumption as the diesel fuel station. The electric truck is assumed to be charged from a charging point and uses lithium-ion batteries. The LNG trailer is assumed to be driven by diesel power tractor unit and to travel 728 km (roundtrip) from LNG import terminals in the UK to the fuel stations, based on calculated average transport distances from LNG terminals to UK fuel stations using Google Maps.

The IPCC AR5 LCIA methodology [33] was used to calculate the impacts to climate change using up-to-date GWP CO_2 equivalences, while ReCiPe LCIA methodology was used to calculate the impacts to air quality and resource depletion (abiotic and fossil) [34]. To assess the effect of methane emissions, the amount of methane slip needed for the GWP to equal diesel was calculated, as well as the sensitivity of total climate impact to changes in methane emissions.

2.2. Data and assumptions

The inventory data for fuel consumption and urban share is shown in Table 1. Literature data on fuel consumption for the natural gas, diesel and other diesel alternative trucks were used in GREET to estimate tailpipe emissions.

To model the fuel stations and LNG trailer, literature data was used to collect data on fuel station energy consumption as well as fugitive emissions. It was assumed the biodiesel and dimethyl ether fuel stations have the same energy consumption as diesel. The UK 2016 electricity mix was used to charge the electric HGV and to meet energy demands at the fuel stations [35, 36]. The UK 2016 natural gas mix [35, 36] was used as the feed stream for CNG and LNG liquefied onsite, while the UK LNG import mix was used for LNG delivered by trailer. For the upstream stages, ecoinvent datasets were used. The datasets were used as is but were modified where necessary to use UK electricity (to make as UK specific as possible).

Table 1: Fuel consumption and urban share of trucks considered. Sources: [37-42].

Fuel[a]	Fuel consumption [b] (MJ/km)	Urban share
CNG	13.3-26.1	0.36
LNG	13.0-18.7	0.36
Dual fuel (LNG and diesel)	18.1-18.5	0.36
Diesel	10-17.4	0.36
Biodiesel	10.5-20.2	0.36
Dimethyl ether	6.5-11.8	0.36
Electric[c]	4.5	0.36

[a]the truck body was not considered in the LCA model as HGV have high lifetime mileage, such that impacts of the truck body would be insignificant.
[b]based on HHV for liquid fuels
[c]lithium ion battery

Table 2: CNG, LNG and diesel fuel station energy and emissions specifications. Sources: [17, 25-27].

	CNG	LNG	Diesel
Fuel station energy demand (MJ/GJ fuel)	231	192	7.9×10^{-3}
Liquefaction energy (kWh/ kg)	-	0.15	-
LNG cooling (kWh/ kg)	-	0.1	-
Fuel station fugitive emissions (kg/MJ) (% of throughput)	1.86×10^{-7} (1×10^{-5}%)	1.12×10^{-7} (7×10^{-5}%)	-
Fuel station boil-off	0%	0%	-
LNG trailer boil-off	-	0%	-

LNG boil-off at the fuel station and in the trailer are assumed to be zero, as it has been assumed the throughput of the fuel station is such that there is there is no time for boil-off to occur. Similarly, the transit of the LNG trailer is assumed to take less than the time needed for boil-off to initiate (estimated to be 5 days) [43]. In reality there may be boil-off at the fuel station and trailer and the rate of boil-off is affected by external conditions (e.g. outside air temperature) and is further investigated in the sensitivity analysis.

3. Results

3.1. Climate change

Of the natural gas options, LNG (trailer; T and onsite liquefaction; OSL) exhibits a lower global warming potential (GWP) (17-21%) than diesel, as shown in Figure 2. However, for both gas options, the high fuel consumption scenarios reduces the GWP benefit to nil, as shown by the error bars. CNG and dual fuel, on the other hand, have a higher GWP (11-52%), with CNG only comparable with diesel under the lowest fuel consumption scenario. Increased emissions associated with dual fuel is due to the increased fuel consumption overall. In comparison to other diesel alternatives, LNG (T and OSL) have lower GWP than dimethyl ether and is comparable to electric (UK electricity mix). Biodiesel has the lowest GWP of all the options considered; six times lower than diesel and five times lower than LNG. CNG has the highest GWP of all the options.

The life cycle stage which contributes the most towards the GWP is, the combustion of fuel in the truck (Figure 3) for CNG, LNG T, LNG OSL, dual fuel T, dual fuel OSL, diesel and dimethyl ether. The second most impactful stage is the electricity (both compressing and liquefying gas and energy to run fuel dispensing equipment (fuel station in Figure 3) used by the fuel station, followed by fuel production for the dedicated natural gas truck. For the other fossil fuel trucks and dimethyl ether the fuel production stage is the second most impactful stage. For biodiesel, the production of fuel is the main source of greenhouse gas emissions while for the electric truck, electricity to charge the truck contributes the most.

3.2. Methane sensitivity

The impact of methane emissions on the overall GWP of CNG and LNG (dedicated) is presented, considering the effect of methane slip and emissions in the supply chain.

3.2.1. Methane slip

Figure 4 shows the impact of different methane emissions on the GHG emissions of LNG. As shown, there is a broad variation of the impact of methane emissions, governed by the fuel efficiency. On average, methane emissions must be kept below 3.1-3.5% of throughput (7.8-9.0 g CH_4/km) to ensure a climate benefit over diesel (Figure 5). With high fuel consumption, methane slip must be effectively zero to reach parity, whilst with lower fuel consumption methane must be kept below 5.5-6.0% of throughput (12.4-13.3 g CH_4/km) for OSL and T, respectively. However, these are much higher than measurements of slip from current natural gas trucks (≤0.5 g CH_4/km of throughput). For CNG, only under the lowest fuel consumption and low methane slip (2.2% of throughput) does CNG become comparable to diesel. Therefore, slip is not likely to have a significant impact on the GWP of current natural gas trucks, except when fuel consumption is high. The impact of emissions in the supply

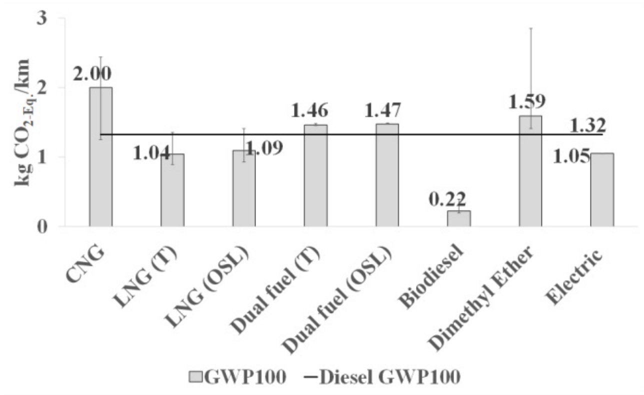

Figure 2: Global warming potential (GWP) over 100-year time horizon of natural gas and other diesel alternatives. The bars show the average GWP and the error bars the range in GWP. The GWP is proportional to fuel consumption; the lower limit represents the lowest fuel consumption while the upper limit represents the highest fuel consumption. The average GWP of diesel is shown in the figure. The maximum GWP of diesel is 1.51 kg $CO_{2\text{-}Eq.}$/km and the minimum is 0.87 kg $CO_{2\text{-}Eq.}$/km.

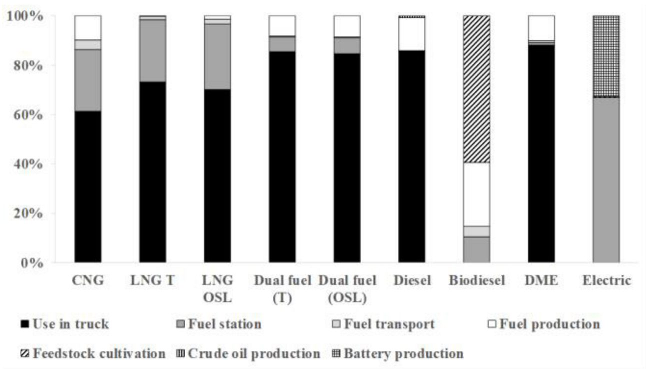

Figure 3: 'Hot spot' analysis of GWP, showing which stages contribute what towards the GWP for natural gas, diesel and other diesel alternatives.

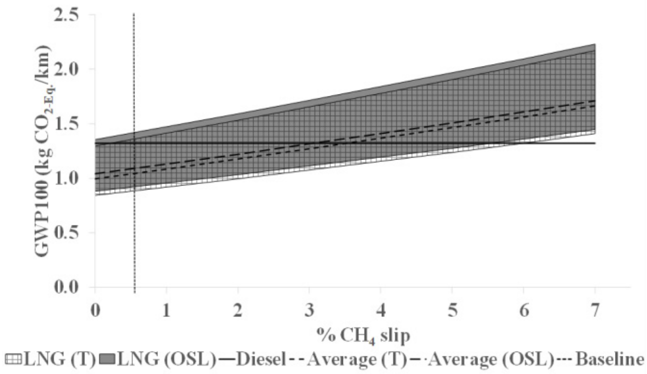

Figure 4: Variation in GWP with methane slip for dedicated LNG truck for LNG delivered via trailer and liquefied on site.

chain also effects the climate benefits but was found to be less impactful than methane slip.

3.3. Air quality

The impacts to air quality are measured through particulate matter formation potential and photochemical ozone formation potential, as shown in Figure 5. In comparison to diesel, LNG (dedicated and dual fuel) trucks have lower impacts for both indicators (37-61%) and LNG T is the lowest of all the options. CNG is higher only for particulate matter (21%); photochemical ozone is lower (15%).

Out of the non-natural gas options, the electric battery HGV has higher impacts than diesel and CNG, as can be seen in Figure 5. From a hot spot analysis, this is because of the electricity mix as coal has high impacts for air quality [44]. Dimethyl ether is on par with LNG, whilst the biodiesel truck has the highest impact for photochemical ozone but is on par with LNG dual fuel for particulate matter. The hot spot analysis found that this is because of the processing needed to make the fuel, as well as cultivating the feedstock and producing a crude oil from the feedstock.

3.4. Resource depletion

The impacts to resource depletion is measured through two indicators: metal depletion and fossil fuel depletion. All the LNG trucks have lower resource depletion than diesel as shown in Figure 6 (11-66%). The values are similar to diesel for the dual fuel while for the dedicated, there is a more noticeable benefit over diesel with LNG T having the lowest impact for both indicators out of all the natural gas options. The difference is due to the use of diesel in the dual fuel truck. CNG is 72% higher for metal depletion but is 13% lower for fossil depletion. The other diesel alternatives have higher impact that diesel for metal depletion, as shown in Figure 6. A hot spot analysis found that this is due to the resources needed to produce the fuel and battery; the electric truck has the highest impact for metal depletion due to the rare earth metals needed to make the battery, as well as fossil depletion (Figure 6) because of the fossil fuels in the UK electric mix and efficiency of fossil fuel power plants.

4. Limitations, uncertainty and scope for future work

The results of the study are limited to the data used. As a result, the impact of driving regime, road type, weather conditions, truck load, age of truck and condition of truck are not considered. These factors would all effect the environmental impacts of all the trucks considered in this work. To account for uncertainty, a wide range in fuel consumptions has been considered (where possible and results indicated by error bars in Figures 2 and 5-6) and a sensitivity analysis on methane emissions conducted. The non-CO_2 tailpipe emissions are limited to data from GREET, which are fixed for the various vehicles in their database. Therefore, variations in exhaust emissions would not be considered. As literature data from various sources was used, the study also does not compare like-for-like engines and trucks (same manufacturer, engine size etc.), which adds additional uncertainty. To reduce uncertainty future work should collect data from natural gas and comparable diesel and alternative fuel trucks. The trucks should be comparable is not like-for-like. The same driving regime (route, speed along various roads and conducted on the same day) should be used and all trucks should carry the same load.

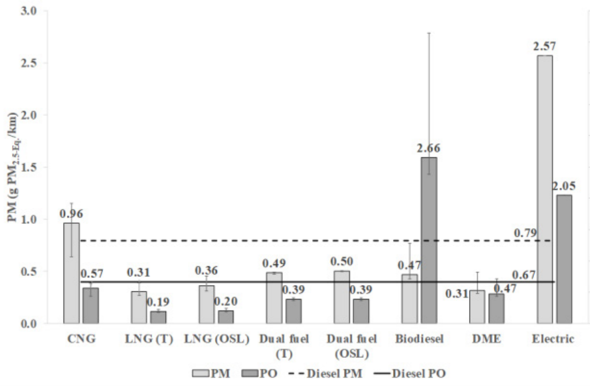

Figure 5: Impacts to air quality for natural gas and other diesel alternatives, in comparison to diesel. The life cycle impact assessment (LCIA) indicators particulate matter (PM) and photochemical ozone (PO) formation potential are considered. These indicators measure the potential for the emissions of air pollutants which could result in the formation of PM or PO. The average impacts of diesel are shown in the figure. The maximum impacts of diesel are 0.92 g $PM_{2.5\text{-}Eq.}$/km and 7.0 g $NO_{x\text{-}Eq.}$/km and the minimum impacts are 0.63 g $PM_{2.5\text{-}Eq.}$/km and 5.9 g $NO_{x\text{-}Eq.}$/km.

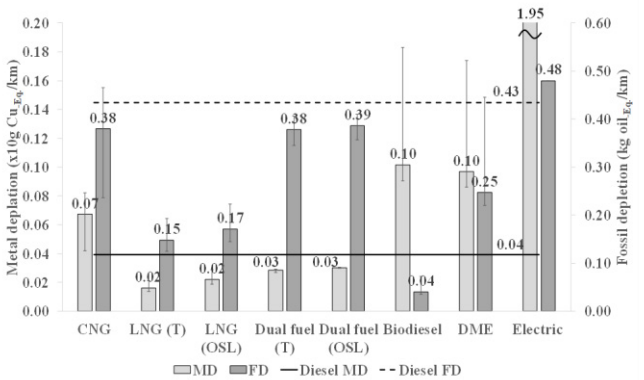

Figure 6: Impacts to resource depletion for natural gas and other diesel alternatives, in comparison to diesel. Metals (and other abiotic resources) depletion (MD) and fossil fuel resource depletion (FD) potentials are considered. The average impacts of diesel are shown in the figure. The maximum impact of diesel are 0.45 g $Cu_{Eq.}$/km and 0.50 kg $oil_{Eq.}$/km and the minimum impacts are 0.26 g $Cu_{Eq.}$/km and 0.24 kg $oil_{Eq.}$/km.

5. Conclusions

The environmental impacts of various fuels for HGVs have been assessed, including CNG, LNG (dedicated and dual fuel), diesel, biodiesel, dimethyl ether and electric. Of all the natural gas options considered, if a dedicated LNG engine is used reductions across all environmental indicators are achievable. Dual fuel options, despite having lower impacts for air quality and resource depletion, have higher impacts for climate change. CNG, performs poorly for most indicators compared to diesel but is on par for the lowest fuel consumption figures considered here.

The effect of methane emissions was analyzed through a sensitivity analysis of methane slip. In order for natural gas to be on par with diesel in terms of climate change, under average fuel consumptions methane slip must be kept under 3.5% of throughput for LNG. This is much higher than measurements of slip from current natural gas trucks in use, from which a maximum of 0.5 g CH_4/km slip has been recorded. However, if fuel consumption increases to 18.7 MJ/km, methane emissions must be effectively zero for LNG. For CNG, only under the lowest fuel consumption and methane emissions under 2.2% of throughput, does this option reach parity with diesel.

Under central methane and fuel consumption conditions, LNG results in a climate reduction of 17-21% compared to diesel, which is comparable to the electric truck. Air quality impacts are also relatively low for the natural gas options. In comparison to other diesel alternatives, LNG has lower impacts than dimethyl ether for climate change; biodiesel and electric for air quality (particulates and photochemical ozone formation); biodiesel, dimethyl ether and electric for metal depletion and electric for fossil depletion. CNG has the highest impact for climate change; biodiesel and electric the highest for air quality; electric the highest for resource depletion.

Based on the results of this work, natural gas may offer GHG reductions of up to 21% but is highly dependent on methane emissions, the fuel delivery method and the fuel consumption. Additionally, natural gas exhibits lower impacts for most of the other indicators considered. Therefore, natural gas is a viable option for decarbonizing and reducing air pollution. However, by itself it is not enough to meet emission targets set by various governments. The adoption of natural gas in the road freight sector will depend on government policies, truck technologies and fuel prices. If it were to be used, its role would be temporary and as a transition fuel to shift the freight industry from diesel reliance to zero tailpipe emission; electric and hydrogen fuel cell but only if electricity mix is decarbonized and hydrogen is produced from renewable feedstock to minimize impacts to climate change, air quality and resource depletion.

Acknowledgements

The authors would like to acknowledge the funding from the Sustainable Gas Institute, founded by Imperial College London and BG Group (now part of Royal Dutch Shell). Funding for the Sustainable Gas Institute is gratefully received from Royal Dutch Shell, Enagás S.A. and the Newton/NERC/FAPESP Sustainable Gas Futures project NE/N018656/1.

Note, the funding bodies were not involved in the design, implementation or reporting of this study.

References

[1] IEA, 2017, *CO2 emissions from fuel combustions*, International Energy Agency (IEA), Paris, FR. Available from: https://www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustionHighlights2017.pdf.

[2] IEA, 2017, *The future of trucks: Implications for energy and the environment* International Energy Agency (IEA), Paris, FR. Available from: http://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf.

[3] Statista, 2018, *Number of passenger cars and commercial vehicles in use worldwide from 2006 to 2015 in (1,000 units)*, Statista, London, UK, Available from: https://www.statista.com/statistics/281134/number-of-vehicles-in-use-worldwide/.

[4] icct, 2016, *A technical summary of Euro 6/VI vehicle emission*

standards The International Council on Clean Transportation (icct), Berlin, DE. Available from: https://www.theicct.org/publications/technical-summary-euro-6vi-vehicle-emission-standards.

[5] EIA, 2018, *Gasoline and diesel fuel update*, E.I.A. (EIA), Washington, D.C., USA, Available from: https://www.eia.gov/petroleum/gasdiesel/.

[6] World Bank, 2018, *Pump price for diesel fuel (US$ per litre)*, W. Bank, Washington, D.C., USA, Available from: https://data.worldbank.org/indicator/EP.PMP.DESL.CD.

[7] Hassan, M.H. and M.A. Kalam, *An Overview of Biofuel as a Renewable Energy Source: Development and Challenges.* Procedia Engineering, 2013. **56**: p. 39-53.

[8] Bonges, H.A. and A.C. Lusk, *Addressing electric vehicle (EV) sales and range anxiety through parking layout, policy and regulation.* Transportation Research Part A: Policy and Practice, 2016. **83**: p. 63-73.

[9] EIA. *How much carbon dioxide is produced when different fuels are burned* 2018 [cited: 2018 June 2018]; Available from: https://www.eia.gov/tools/faqs/faq.php?id=73&t=11.

[10] IGU. *Natural gas is the cleanest fossil fuel*. 2017 2017 [cited: 2018 June 2018]; Available from: https://www.igu.org/natural-gas-cleanest-fossil-fuel.

[11] Yedla, S., *Urban transportation and the environment: Issues, alternatives and policy analysis*. 2015, New Delhi, IN: Springer.

[12] FT. *Commodities*. Markets data 2018 [cited: 2018 June]; Available from: https://markets.ft.com/data/commodities/tearsheet/summary?c=Natural+Gas.

[13] AFDC. *Natural gas benefits and considerations*. 2018 [cited: 2018 June]; Available from: https://www.afdc.energy.gov/fuels/natural_gas_benefits.html.

[14] AFDC. *Natural gas vehicles*. 2018 [cited: 2018 June]; Available from: https://www.afdc.energy.gov/vehicles/natural_gas.html.

[15] NGV Global. *Engine types*. 2018 [cited: 2018 June]; Available from: http://www.iangv.org/natural-gas-vehicles/engine-types/.

[16] NGV Global, 2018, *Current natural gas vehicle statistics*, N.G.V.N.K. Base, Remuera, NZ, Available from: http://www.iangv.org/current-ngv-stats/.

[17] Arteconi, A., et al., *Life-cycle greenhouse gas analysis of LNG as a heavy vehicle fuel in Europe.* Applied Energy, 2010. **87**(6): p. 2005-2013.

[18] Beer, T., et al., *Fuel-cycle greenhouse gas emissions from alternative fuels in Australian heavy vehicles.* Atmospheric Environment, 2002. **36**(4): p. 753-763.

[19] Bicer, Y. and I. Dincer, *Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles.* Resources, Conservation and Recycling, 2018. **132**: p. 141-157.

[20] Cai, H., et al., *Wells to wheels: Environmental implications of natural gas as a transportation fuel.* Energy Policy, 2017. **109**: p. 565-578.

[21] Huo, H., et al., *Climate and Environmental Effects of Electric Vehicles versus Compressed Natural Gas Vehicles in China: A Life-Cycle Analysis at Provincial Level.* Environmental Science & Technology, 2013. **47**(3): p. 1711-1718.

[22] Shahraeeni, M., et al., *Life cycle emissions and cost of transportation systems: Case study on diesel and natural gas for light duty trucks in municipal fleet operations.* Journal of Natural Gas Science and Engineering, 2015. **24**: p. 26-34.

[23] Sharma, A. and V. Strezov, *Life cycle environmental and economic impact assessment of alternative transport fuels and power-train technologies.* Energy, 2017. **133**: p. 1132-1141.

[24] Tong, F., P. Jaramillo, and I.M.L. Azevedo, *Comparison of Life Cycle Greenhouse Gases from Natural Gas Pathways for Light-Duty Vehicles.* Energy & Fuels, 2015. **29**(9): p. 6008-6018.

[25] Bates, J., et al., 2014, *Waste and gaseous fuels in transport - Final report*, Ricardo-AEA for the Department for Transport, London, UK. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/336022/gasesous-fuels-report.pdf.

[26] John Norris, C.B., Ben White, Andrea Demurtas, Anthony Sale, Ian Dawson, 2015, *Provision of HGV emissions testing*, Ricardo-AEA for the Department for Transport, London, UK. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/468172/hgv-emissions-testing.pdf.

[27] Robinson, B., 2017, *Emissions testing of gas-powered commercial vehicles*, Low Carbon Vehicle Partnership (LowCVP) for the Department for Transport, London, UK. Available from: https://www.gov.uk/government/publications/emissions-testing-of-gas-powered-commercial-vehicles.

[28] ISO, *ISO 14040:2006*. 2006, International Organization for Standardization (ISO): Geneva, CH.

[29] ISO, *ISO 14044:2006*. 2006, International Organization for Standardization (ISO): Geneva, CH.

[30] thinkstep, *GaBi Professional* 2018: Echterdingen, DE.

[31] ecoinvent, 2018, *ecoinvent 3.3*, ecoinvent, Zurich, CH, Available from: https://www.ecoinvent.org/database/database.html.

[32] Argonne National Laboratory, *GREET*. 2017, Argonne National Laboratory: Lemont, IL, USA.

[33] IPCC, 2014, *Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*, Intergovernmental Panel on Climate Change (IPCC), Geneva, CH. Available from: http://ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/IPCC_SynthesisReport.pdf.

[34] Huijbregts, M.A.J., et al., 2016, *ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level*, National Institute for Public Health and the Environment Bilthoven, NL. Available from: https://www.rivm.nl/Documenten_en_publicaties/Wetenschappelijk/Rapporten/2016/december/ReCiPe_2016_A_harmonized_life_cycle_impact_assessment_method_at_midpoint_and_endpoint_level_Report_I_Characterization/Download/ReCiPe_2016_A_harmonized_life_cycle_impact_assessment_method_at_midpoint_and_endpoint_level_Report_I_Characterization.pdf.

[35] BEIS, 2017, *UK energy in brief*, Department for Business, Energy and Industrial Strategy (BEIS), London, UK. Available from: https://www.gov.uk/government/statistics/uk-energy-in-brief-2017.

[36] BEIS, 2017, *Digest of UK energy statistics (DUKES)*, Department for Business, Energy and Industrial Strategy (BEIS), London, UK. Available from: https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2017-main-report.

[37] Burke, A. and H. Zhao, *Fuel economy analysis of medium/heavy-duty trucks: 2015-2050*, in *EVS30 Symposium* 2017, Institute of Transportation Studies: Stuttgart, DE.

[38] Iveco, 2018, *NP- Natural Power*, Iveco, Turin, IT. Available from: https://www.iveco-dealership.co.uk/media/stralis-np/NP%20full%20range%20Brochure.pdf.

[39] Iveco, 2018, *New Stralis NP- pure power*, Iveco, Turin, IT. Available from: https://www.iveco.com/Common/Documents/Brochures/new_stralisNP.pdf.

[40] Cryogas M&T Poland, 2016, *Iveco Stralis LNG natural gas power: Report on testing of Iveco LNG vehicles in Poland*, Cryogas M&T Poland., Warsaw, PL. Available from: https://www.cryogas.pl/pliki_do_pobrania/artykuly/Cryogas_IVECO_Report._Polish_road_tests_.pdf.

[41] Cryogas M&T Poland, 2017, *Test report of Iveco LNG-powered HD-truck*, Cryogas M&T Poland,, Warsaw, PL. Available from: https://www.cryogas.pl/pliki_do_pobrania/artykuly/20171110_Raport_LNG_Unilever_Link_Iveco_.pdf.

[42] Tesla. *Tesla Semi*. 2018 [cited: 2018 June]; Available from: https://www.tesla.com/en_GB/semi.

[43] Gunnarsson, L. *How to handle boil-off gas from LNG trucks*, 2015. Linköping University, *Department of Management and Engineering* Masters Thesis, Linköping, SE

[44] Cooper, J., L. Stamford, and A. Azapagic, *Environmental Impacts of Shale Gas in the UK: Current Situation and Future Scenarios.* Energy Technology, 2014. **2**(12): p. 1012-1026.